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# The applicability of computer simulation using Monte Carlo techniques in windfarm profitability analysis

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ABSTRACT

Obtaining external financing for windfarms may be hindered over the next few years by the high degree of uncertainty that is inherent in these types of project. Therefore, promoters must carefully plan and analyse their projects and attempt to optimise the profitability/risk factor of each investment. The objective of this paper is to demonstrate that Monte Carlo sampling represents an excellent approach to economic risk management in windfarm projects, as it provides a practical method of calculating the distribution of the NPV via the various random input variables. To this end, we defined a windfarm model, which has also allowed us to identify the basic parameters of current projects of this nature in Spain. We analysed the profitability of these projects using Monte Carlo techniques.



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## 1. Introduction

Over the course of the last ten years, wind energy in Spain has experienced an extraordinary upsurge and Spain is currently one of the leading countries at global level in terms of installed capacity. Indeed, with more than 10,000 MW installed at the end of 2005 and having covered 20% of the electricity demand, Spain has already surpassed the objective set for 2010 in the Plan to Promote Renewable Energies (PLAFER) [1].

The new 2005–2010 Renewable Energy Plan (PER) [2], passed by the Council of Ministers on the 26th of August 2005, reflects this success with a significant increase in the national objective: installed capacity for 2010 is set to reach 20,155 MW, with an energy increase of 12,000 MW between 2005 and 2010 [3,4]. Achieving this goal, which requires significant investment, depends upon the continued stability of salaries and the willingness of banks to provide financing [5].

A previous research paper [6] focused on the determining factors affecting the economic viability of wind energy projects in Spain in

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the short term. On the basis of this analysis, it was concluded that the ability to obtain third-party financing for windfarms will be impeded over the next few years by the existence of considerable levels of uncertainty, which forms an inherent part of these projects and may lead to saturation amongst the main banks, or, at the very least, a more stringent selection process for funding [7].

Therefore, promoters must carefully plan and analyse their projects in an attempt to optimise the profitability/risk factor of each investment, and avoid the construction of inefficient windfarms with high levels of risk as these types of installations may become a serious obstacle to development and financing in the short term. In other words, we need to study the possibility of carrying out financial analysis that is more exhaustive than the analysis employed in traditional evaluation methods, given that these methods operate in conditions of certainty, with the supposition that predictions will coincide with reality.

The aforementioned article examined the various models used to evaluate investment in risk conditions with the aim of choosing an ideal tool for decision-making in the context of risk or uncertainty. Statistical simulation methods, in particular the Hertz Model and Monte Carlo Simulation, proved to be most suitable as they were able to incorporate the highly random nature of wind as a resource.

This statistical simulation technique permits in-depth analysis of the sensibility of the investment. That is, rather than taking fixed average values for all the inputs that define profitability, certain inputs are considered as random variables with the corresponding probability functions, and the different profitability index values (Net Present Value, Internal Rate of Return) are calculated on the basis of the various possible values of these inputs. This iterative process generates the probability distributions of the profitability indexes.

This provides more in-depth knowledge on the projects as risk is measured in the form of a variation range for the result, thereby improving the quality of decisions and confidence in the same [8]. Moreover, this facilitates comparison of investment alternatives without the need of using the concept of expected utility, which is impractical in view of the extreme difficulty of assigning utility values for all possible results.

Therefore, it is our intention to carry out a specific application of these techniques in a model windfarm project, comparing results obtained via analysis involving simulation with those obtained via traditional analysis techniques.

## 2. Applicability of Monte Carlo sampling in windfarm profitability analysis

To define the Model Project we took the aforementioned 2005–2010 Renewable Energy Plan (PER) as a starting point. Chapter 4 of the Plan, dedicated to the Financing of renewable energy installations, includes Model Cases for windfarm installations, indicating the basic parameters for economic and financial analysis of a windfarm project. The points made by APPA [9] with regards to the factors that influence the profitability of these types of investments have also been taken into consideration.

Having defined the initial basic characteristics of our Model Project, we will proceed to carry out profitability analysis using traditional techniques in conditions involving no uncertainty and considering all inputs as deterministic variables. This will provide us with a single average value for each of the profitability indexes of the investment (NPV, IRR).

Subsequently, and as we have stated, we will apply a computer simulation using Monte Carlo techniques in order to simulate the economic risk of the project. In this case, certain inputs will become random variables. The probability descriptions of the random input variables and the Monte Carlo sampling will provide us with the probability distributions of the desired outputs. This risk analysis will be referred to as a Simulated Project.

**Table 1**
Parameters for a model Spanish installation with a 5 MW capacity (outlined in the Renewable Energies Plan).

| | |
|---|---|
| Model case and per evolution hypothesis for 2005–2010 | |
| Power: | 5 MW |
| Investment ratio: | 937 €/kW (annual evolution +1.8%) |
| Equivalent no of hours of production | 2350 h/year |
| Life-span | 20 years |
| Operating costs | 1.47 cent€/kWh (evolution RPI −0.5%) |
| Dismantling costs | 3.5% s/investment |
| Electricity sale price: | Invoicing with regulated tariff<br>Year 1–15.90% TMR<br>Remainder 80% TMR |
| Average reference tariff, TMR (2005) | 7.3304 cent€/kWh |
| Annual TMR evolution | 1.40% |
| Investment breakdown | |
| Promotor: | 20% of the investment |
| Third party financing | 80% of the investment |
| Subsidy | Not specified |
| Support | |
| Subsidy based on market price | 40% TMR |
| Subsidy: | Not specified |
| Market participation incentive | 10% TMR |
| Tax incentives | |
| None specified | |
| Applicable forms of financing | |
| Project finance | |

## 3. Model project

### 3.1. Characteristics of the model project according to PER

The main parameters for a model Spanish installation with a 5 MW capacity, as outlined in the Renewable Energies Plan (PER), are shown in Table 1. We will use these parameters as a basis on which to define our Model Project. These figures can be used to comment on the current situation of Spanish windfarms:

Spanish technology has reached maturity, which, considered along with the fact that wind generators have reached levels of virtual mass production, has led to a significant decrease in the construction and installation costs of windfarms. Nevertheless, over recent years there has been a slight tendency towards cost increases, which, amongst other factors, can be attributed to the installation of high capacity wind generators that are not massed produced at general level.

In Spain, wind generators account for approximately three quarters of the total current investment associated with windfarms, whilst electrical and mechanical equipment (including transport lines) and construction work account for 17% and 5% respectively. The remaining 4% is made up of assorted investments such as evaluation studies focusing on wind resources, environmental impact, promotion, licence processing and engineering.

Running costs have also experienced a reduction over recent years, whilst the reliability, facilities and guarantees offered by technologists have become more consolidated. Running costs represent approximately 22% of a farm's annual turnover. Operating costs and maintenance account for 57% of these costs, and the remainder is made up of land rental (16%), insurance and taxes (14%) and management and administration (13%).

In terms of windfarm revenue, Royal Decree RD 436/2004 [10] establishes two remuneration alternatives for the electrical energy that is produced:

**Table 2**
Regional wind climate summary.

| Height | Parameter | 0.00 m | 0.03 m | 0.10 m | 0.40 m |
|---|---|---|---|---|---|
| 10.0 m | Weibull A [m/s] | 8.2 | 5.7 | 5.0 | 3.9 |
| | Weibull k | 2.33 | 2.03 | 2.03 | 2.04 |
| | Mean speed [m/s] | 7.25 | 5.08 | 4.44 | 3.50 |
| | Power density [W/m$^2$] | 388 | 152 | 101 | 49 |
| 25.0 m | Weibull A [m/s] | 8.9 | 6.8 | 6.2 | 5.2 |
| | Weibull k | 2.38 | 2.15 | 2.14 | 2.14 |
| | Mean speed [m/s] | 7.93 | 6.06 | 5.46 | 4.59 |
| | Power density [W/m$^2$] | 499 | 243 | 178 | 106 |
| 50.0 m | Weibull A [m/s] | 9.6 | 7.9 | 7.2 | 6.2 |
| | Weibull k | 2.44 | 2.35 | 2.32 | 2.28 |
| | Mean speed [m/s] | 8.50 | 6.98 | 6.38 | 5.52 |
| | Power density [W/m$^2$] | 605 | 344 | 265 | 174 |
| 100.0 m | Weibull A [m/s] | 10.4 | 9.3 | 8.5 | 7.5 |
| | Weibull k | 2.38 | 2.51 | 2.53 | 2.54 |
| | Mean speed [m/s] | 9.19 | 8.22 | 7.55 | 6.63 |
| | Power density [W/m$^2$] | 778 | 535 | 413 | 278 |
| 200.0 m | Weibull A [m/s] | 11.4 | 11.4 | 10.4 | 9.1 |
| | Weibull k | 2.29 | 2.44 | 2.46 | 2.50 |
| | Mean speed [m/s] | 10.12 | 10.10 | 9.22 | 8.04 |
| | Power density [W/m$^2$] | 1070 | 1012 | 766 | 503 |

(1) Selling the electricity to the distribution company at a regulated rate, wherein the price will depend on the capacity and the number of years that the installation has been in operation.
(2) Open sale on the market. This option offers two possibilities: accessing the market directly via a system of offers managed by the market operator, or via a contract with a marketing company. In any event, a subsidy is added to market spot prices.

The established amounts for the regulated rate and the subsidy are indexed to the so-called Average Reference Tariff (TMR), which is established via decree on an annual basis, representing the relationship between the foreseen cost requirements to pay for activities relating to electricity supply and predicted end-user demand.

### 3.2. Estimating mean annual energy production

Given a regional wind climate, the wind climate at any specific site and height can be evaluated using Wind Atlas Analysis and Application Program (WAsP) [11,12]. The WAsP software is an implementation of the so-called wind atlas methodology. By introducing descriptions of the terrain around the predicted site, the WAsP models can predict the actual, expected wind climate at this site:

- regional wind climate + site description → predicted wind climate (PWC)

The regional wind climate for our Model Project is shown in Table 2, which contains wind distributions for 4 reference roughness lengths (0.000 m, 0.030 m, 0.100 m, 0.400 m) and 5 reference heights (10 m, 25 m, 50 m, 100 m, 200 m) above ground level [13]:

In terms of installation layout, we will assume that it contains five 1 MW wind generators. The WasP program allows us to identify the most suitable locations for each of the wind turbines. This is referred to as a micrositting study [14–16]. The results are shown in Fig. 1: Micrositting of wind turbines generated by WAsP.

The predicted wind climate of each wind turbine site is given in terms of the wind rose and the wind speed distributions for each sector and in total [17]. WAsP calculates the following data (for each sector and in total) for the site:

- the frequency of occurrence
- the Weibull A-parameter
- the Weibull k-parameter
- the mean wind speed
- the mean power density

For example, Fig. 2, shows predicted wind climate, that is, the probability density function of wind speed at hub height at wind turbine site 1:

All that remains is to calculate mean power production for each turbine employing the mean wind. The sum of these figures will provide the mean expected production of the Model Project, which will allow us to calculate the profitability of the same. For this purpose we require the power curve of the turbines:

- predicted wind climate + power curve → annual energy production of wind turbine

The wind turbine model chosen for the Model Project has a cut-in velocity of 4 m/s and a cut-off velocity of 25 m/s, with the power curve shown in Fig. 3:

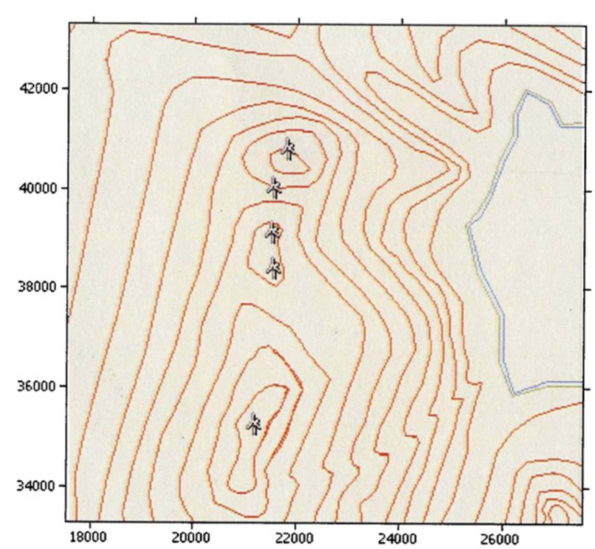



**Fig. 1.** Micrositting of wind turbines (generated by WAsP).

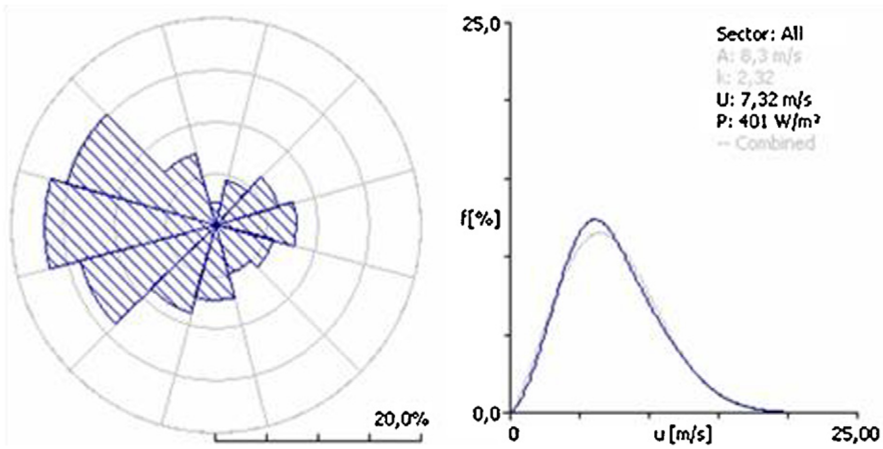



**Fig. 2.** Predicted wind climate (generated by WAsP).

Thus, the mean power production of each turbine can be expressed as follows:

$$P = \int_0^\infty \Pr(U) \cdot P(U) dU$$

Where $\Pr(U)$ is the probability density function of the wind speed at hub height and $P(U)$ is the power curve of the turbine.

Given that the probability density function, $\Pr(U)$, has been calculated as a Weibull function, the aforementioned equation is transformed as follows:

$$P = \int_0^\infty \left(\frac{k}{A}\right) \cdot \left(\frac{U}{A}\right)^{k-1} \cdot \exp\left(-\left(\frac{U}{A}\right)^k\right) \cdot P(U) dU$$

Moreover, actual power curves are rather smooth and can be well approximated by a piece-wise linear function with a few nodes:

$$P(U) = \frac{P_{i+1} - P_i}{U_{i+1} - U_i}(U - U_i) + P_i$$

which allows for an analytical solution of the integral:

$$P = \sum_i \frac{P_{i+1} - P_i}{\alpha_{i+1} - \alpha_i}(G_k(\alpha_{i+1}) - G_k(\alpha_i))$$

where $\alpha_i = U_i/A$. The function $G_k(\alpha)$ is $1/k$ times the incomplete gamma function of the two arguments $1/k$ and $\alpha^k$.

WAsP makes these calculations automatically. Table 3 shows the mean annual energy productions for each turbine, and the overall energy produced by the farm. This mean value will be used to calculate the profitability of the investment under conditions wherein no uncertainty exists.

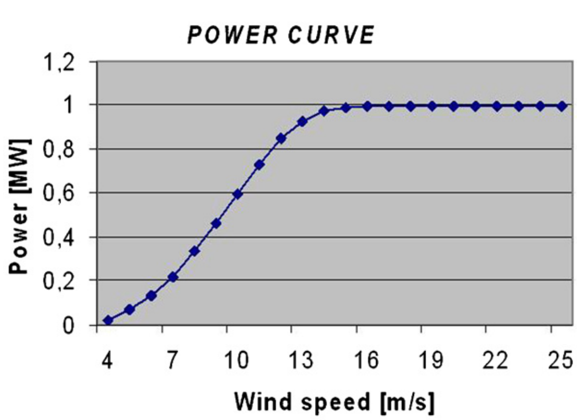



**Fig. 3.** Power curve (generated by WAsP).

### 3.3. Energy sale price

As mentioned above, Royal Decree RD 436/2004 outlines two alternatives for the remuneration of electrical energy: regulated tariff, or market prices with a subsidy. The latter option, which is usually chosen as it proves more beneficial, is considered below.

Thus, the tariff is calculated as follows:

$$\text{Electricity tariff} = \text{Market Price} + \text{Subsidy} + \text{Market Participation Incentive}$$

Wherein,

Market price: definitive spot price published each month by the Market Operator (OMEL).

Subsidy: 40% TMR (mean or reference Tariff)
Market participation incentive: 10% TMR

Thus, for 2006, the market price is established as 3.965 cent€/kWh, which represents the average market price between 1998 (the year in which the Spanish market was set in motion) and 2005. The TMR for 2006 has been set at 7.6588 cent€/kWh in Royal Decree RD 1556/2005 [18]. Thus, energy sale price is calculated as follows:

2006 Tariff = 3.965 + 0.4*7.6588 + 0.1*7.6588 = 7.794 cent€/kwh

The same average market price will be used for the remaining years during which the farm is in operation. In terms of subsidies, the mean or reference Tariff (TMR) will be increased by +1.4% on an annual basis, in accordance with the 2005–2010 PER.

**Table 3**
Mean annual energy productions for each turbine, and the overall energy produced by the farm.

| Wind turbine | Location [m] | Height [m] | AEP [GW h] |
|---|---|---|---|
| 1 | (22027, 40987) | 50 | 2.78 |
| 2 | (21834, 39947) | 50 | 2.85 |
| 3 | (21804, 39003) | 50 | 2.88 |
| 4 | (21847, 38027) | 50 | 2.92 |
| 5 | (21134, 35223) | 50 | 3.18 |
| Entire wind farm | | | 14.60 |

**Table 4**
Inputs for the Model Project as deterministic variables.

| | | |
|---|---|---|
| **MODEL PROJECT** | | |
| **ECONOMIC / FINANCIAL ANALYSIS** | | |
| **TECHNICAL CHARACTERISTICS** | | |
| Installed Capacity | 5 | MW |
| Mean Annual Production | 14,6 | GWh/year |
| Life span | 20 | years |
| **ECONOMIC DETAILS** | | |
| Initial annual energy price (Market price + subsidy) | 7,794 | cent€/kWh |
| Market price | 3,965 | cent€/kWh |
| Subsidy + Market Participation Incentive | 0,5*TMR | cent€/kWh |
| Average Reference Tariff (TMR) year one | 7,659 | cent€/kWh |
| Annual Evolution of TMR | 1,4 | % |
| Investment | 4,685 | Million € |
| Operating Costs | 1,47 | cent€/kWh |
| Annual Evolution of Operating Costs | 2,5 | % |
| Mean Retail Price Index | 3 | % |
| Amortization period | 10 | years |
| Value Added Tax | 16 | % |
| Company Tax | 35 | % |
| Fund Operation Requirements | 15 | % |
| Discount Rate | 8 | % |
| **Financial Details** | | |
| Internal Resources | 80% | |
| External Resources | 20% | |
| Subsidies | 0% | |
| TOTAL | 100% | |
| Credit | | |
| Interest Rate | 6% | |
| Years | 10 | |

### 3.4. *Profitability analysis in conditions involving no uncertainty*

Having established all inputs for the Model Project as deterministic variables (Table 4), all that remains is to calculate the profitability indexes of the investment, the Net Present Value and the Internal Rate of Return [19,20]. To this end, we created an electronic spreadsheet that will allow us to calculate the magnitudes that define the indexes:

- Cost evaluation
- Profit evaluation
- Cash flow generated by the project for the overall period of operation

The profitability analysis in conditions involving no uncertainty is summarised in Table 5. We began with fixed mean values for all project inputs and arrived at a mean expected NPV of 2,943,000 € and an IRR of 30%.

## 4. Simulated project

Having carried out the profitability analysis of the Model Project in conditions involving no uncertainty, taking all inputs as deterministic variables, we proceeded to carry out analysis using Monte Carlo techniques, which allows us to consider the economic risk of our project.

In the Model Project, we took both energy price and production price as fixed estimated values. These values will now be considered as random variables, with a range that includes all possible values rather than a single mean value.

Thus, we randomly select a value from each of the probability distributions for the random input variables and calculate the profitability indexes (Net Present Value, Internal Rate of Return) for these values. By repeating this process numerous times via computer simulation, we obtain the probability distributions of the outputs: the Net Present Value and the Internal Rate of Return of the investment [21].

We have already determined the probability density function of the wind speed at hub height for each turbine, which defines farm output. Therefore, our attention is now turned to identifying the probability distribution that most closely coincided with the market price data that has been amassed since the Spanish market was set up in 1998.

Below, we detail risk simulation in the project and the manner in which we treated output and energy sale price as random variables.

**Table 5**
Profitability analysis in conditions involving no uncertainty.

| OPERATIONAL ASPECTS | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Foreseen inflation for initital estimates: | | | | | | | | | | | | | | | | | | | |
| Initial Prices | | | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 | Year 11 | Year 12 | Year 13 | Year 14 | Year 15 | Year 16 | Year 17 | Year 18 | Year 19 | Year 20 |
| Electricity Tariff (subsidy+pool) | 0,078 | | | | | | | | | | | | | | | | | | | | | |
| Definitive spot price (pool) | 0,040 | | | | | | | | | | | | | | | | | | | | | |
| Reference tariff (TMR) | 0,077 | | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% | 1,40% |
| Operation and Maintenance | 122,33 | | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% |
| Land Rental | 34,34 | | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% |
| Insurance | 30,04 | | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% |
| Management and Administration | 27,90 | | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% | 2,50% |

| ECONOMIC / FINANCIAL ASPECTS | |
|---|---|
| Total Investment | 4.685 |
| Financed with internal resources | 937 |
| Financing involving debt | 3.748 |
| Payback Period | 10 |
| Interest Rate | 6,00% |
| Fund Operation Requirements (NOF) | 15% |
| Discount Rate | 8% |

| RESULTS | | Año 0 | Año 1 | Año 2 | Año 3 | Año 4 | Año 5 | Año 6 | Año 7 | Año 8 | Año 9 | Año 10 | Año 11 | Año 12 | Año 13 | Año 14 | Año 15 | Año 16 | Año 17 | Año 18 | Año 19 | Año 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Overall Operative Investments | | 0 | 1.146 | 1.154 | 1.162 | 1.170 | 1.178 | 1.187 | 1.195 | 1.204 | 1.212 | 1.221 | 1.230 | 1.239 | 1.249 | 1.258 | 1.268 | 1.277 | 1.287 | 1.297 | 1.307 | 1.317 |
| Gross Operational Margin | | 0 | 926 | 928 | 931 | 933 | 935 | 938 | 940 | 942 | 944 | 947 | 949 | 951 | 953 | 955 | 957 | 959 | 960 | 962 | 964 | 965 |
| Net Profit | | 0 | 146 | 162 | 179 | 195 | 211 | 251 | 267 | 284 | 300 | 316 | 617 | 618 | 619 | 621 | 622 | 623 | 624 | 625 | 627 | 628 |
| Available Cash Flow (FCD) | | 0 | 675 | 840 | 833 | 827 | 821 | 801 | 795 | 788 | 782 | 775 | 615 | 617 | 618 | 619 | 620 | 622 | 623 | 624 | 625 | 626 |
| Annual Loan Servicing | | 0 | 588 | 566 | 543 | 521 | 498 | 476 | 454 | 431 | 409 | 386 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Coverage ratio of annual loan servicing (RCSD) | | 0,00 | 1,15 | 1,48 | 1,53 | 1,59 | 1,65 | 1,68 | 1,75 | 1,83 | 1,91 | 2,01 | | | | | | | | | | |
| Coverage ratio for overall outstanding debt (RCTD) | | 1,63 | 1,71 | 1,74 | 1,76 | 1,79 | 1,82 | 1,86 | 1,89 | 1,93 | 1,97 | 0,00 | | | | | | | | | | |
| Annually Allocated Dividends | | 0 | 87 | 222 | 179 | 195 | 211 | 251 | 267 | 284 | 300 | 316 | 617 | 618 | 619 | 621 | 622 | 623 | 624 | 625 | 627 | 628 |
| Investment NPV according to cash flows | | 2.943 | | | | | | | | | | | | | | | | | | | | |
| Investment NPV for shareholder | | 2.458 | | | | | | | | | | | | | | | | | | | | |
| Investment TIR according to cash flows | | 30% | | | | | | | | | | | | | | | | | | | | |
| Investment TIR for the shareholder | | 25% | | | | | | | | | | | | | | | | | | | | |
| Return Period according to cash flow | | Years | | | 3 | | | | | | | | | | | | | | | | | |
| | & | Months | | | 4 | | | | | | | | | | | | | | | | | |
| Return Period for the shareholder | | Years | | | | | 5 | | | | | | | | | | | | | | | |
| | & | Months | | | | | 2 | | | | | | | | | | | | | | | |

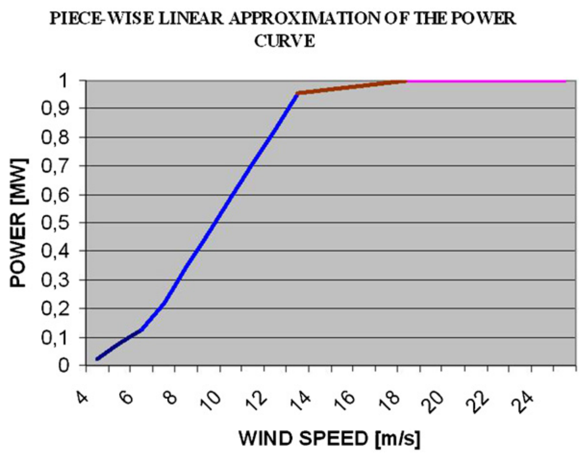



**Fig. 4.** Power curveas a piece-wise linear function involving three nodes of equations.

### 4.1. Output

In the Model Project, output was taken as a fixed single value, the mean expected value obtained via the wind probability distribution. The mean output value was calculated via the following equation:

$$P = \int_0^{\infty} \Pr(U) \cdot P(U) dU$$

where $\Pr(U)$ is the probability density function of the wind speed at hub height and $P(U)$ is the power curve of the turbine.

However, when applying the Monte Carlo simulation, we are no longer interested in calculating the mean value as we will not integrate, rather, we set out directly from the probability description of wind velocity, which is calculated via the Weibull function:

$$\Pr(U) = \left(\frac{k}{A}\right) \cdot \left(\frac{U}{A}\right)^{k-1} \cdot e^{(-(U/A)^k)}$$

For example, the wind probability density function for wind turbine 1 can be expressed as follows:

$$Pr(U) = \left(\frac{2.32}{8.3}\right) \cdot \left(\frac{U}{8.3}\right)^{1.32} \cdot e^{(-(U/8.32)^{2.32})}$$

In each case, wind velocity will be calculated via this probability function, whilst the wind generator power curve will be used to calculate turbine output.

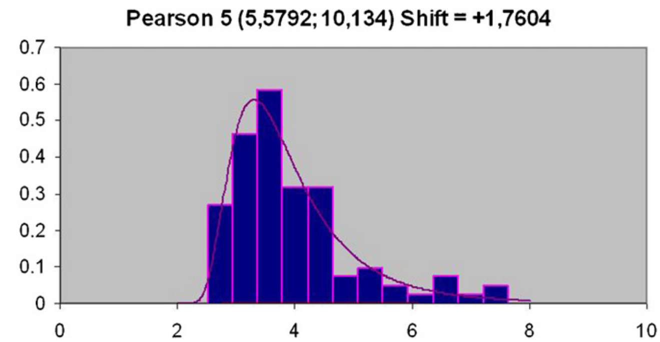



**Fig. 5.** Distribution fitting software.

The power curve can be expressed as a piece-wise linear function involving three nodes (Fig. 4) of equations:

$$P(U)(MW) = \begin{cases} 0.053 \cdot U - 0.191 & 4 \le U < 7 \\ 0.122 \cdot U - 0.634 & 7 \le U < 13 \\ 0.0084 \cdot U + 0.848 & 13 \le U < 18 \\ 1 & 18 \le U < 25 \end{cases}$$

Thus, annual production for each turbine in each iteration can be expressed as follows:

$$U_i \Rightarrow P(U_i) \Rightarrow \text{Annual Production}_i(\text{MWh}) = 8760 \cdot P(U_i)$$

### 4.2. Energy sale price

According to Royal Decree RD 436/2004, energy sale price is made up of two components: market price and the subsidy. The former is what really contributes to risk within the project, given that the subsidy is a percentage of the mean or reference Tariff (TMR), which is approved via decree on an annual basis, with a foreseeable annual increase of 1.4%.

During analysis in conditions wherein no uncertainty exists, market price was taken as a fixed mean value of all definitive spot prices for the entire period over which the Spanish market has been in operation. Given that market price will now be considered as a random variable, we must adapt available data to coincide with a distribution function in order to carry out the simulation.

Table 6 shows the values for definitive spot prices for the period between 1998 and 2005 [22]:

As shown in Fig. 5, distribution fitting software (included in the simulation package) demonstrates that the Pearson 5 parameters was the function that most closely coincides with the historical data:

$\alpha = 5.5792$
$\beta = 10.134$

**Table 6**
Values for definitive spot prices for the period between 1998 and 2005.

| | Definitive spot prices | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | January | February | March | April | May | June | Jury | August | September | October | November | December |
| 1998 | 3.545 | 3.310 | 3.309 | 3.308 | 2.954 | 3.006 | 3.497 | 3.608 | 3.227 | 3.175 | 3.659 | 3.438 |
| 1999 | 3.239 | 3.663 | 3.693 | 3.438 | 3.379 | 3.404 | 3.500 | 3.336 | 3.465 | 3.202 | 3.461 | 3.448 |
| 2000 | 3.863 | 4.098 | 4.389 | 3.770 | 3.118 | 3.410 | 3.494 | 3.355 | 4.450 | 4.423 | 4.209 | 2.796 |
| 2001 | 2.846 | 2.710 | 2.504 | 2.613 | 3.211 | 4.163 | 4.115 | 3.636 | 4.275 | 4.496 | 4.108 | 5.494 |
| 2002 | 6.846 | 4.372 | 4.009 | 4.444 | 4.480 | 4.865 | 5.265 | 3.915 | 4.423 | 4.126 | 3.465 | 2.789 |
| 2003 | 2.759 | 3.271 | 3.080 | 2.758 | 3.115 | 4.412 | 4.385 | 4.505 | 4.441 | 4.107 | 3.249 | 2.826 |
| 2004 | 3.024 | 2.998 | 3.502 | 2.836 | 2.919 | 3.381 | 3.472 | 3.420 | 4.130 | 3.705 | 3.814 | 4.125 |
| 2005 | 4.909 | 5.303 | 6.082 | 5.060 | 5.142 | 6.766 | 7.225 | 5.834 | 6.358 | 5.866 | 6.410 | 7.634 |

**Table 7**
Input variables considered as random in the simulation and their respective probability distributions.

| Input variables | | | |
|---|---|---|---|
| Cell | Name | Current | Formula in cell |
| ! AS18 | Definitive spot price/year i | Pears on 5 (5.5792; 10.134) | =RiskPearson5(5,5792;10,1 34) |
| ! B23 | Turbine 1/year i | Weibull (2.32; 8.3) | =RiskWeibull(2.32.8.3) |
| ! B24 | Turbine 2/year i | Weibull (2.33; 8.4) | =RiskWeibull(2.33;8.4) |
| ! B25 | Turbine 3/year i | Weibull (2.36; 8.4) | =RiskWeibull(2.36.8.4) |
| ! B26 | Turbine 4/year i | Weibull (2.33; 8.5) | =RiskWeibull(2.33;8.5) |
| ! B27 | Turbine 5/year i | Wetbull (2.35; 8.8) | =RiskWeibull(2.35:8.8) |

**Table 8**
Summary of the results of the simulation.

| Summary statistics | | | | | |
|---|---|---|---|---|---|
| Cell | Name | Minimum | Mean | Maximum | Model project |
| E68 (Sim#1) | NPV de la inversion (s/flujos) | −345.19 | 1582.81 | 4199.11 | 2943 |
| E68 (Sim#2) | NPV de la inversion (s/flujos) | −121.20 | 1813.79 | 3673.36 | |
| E68 (Sim#3) | NPV de la inversion (s/flujos) | 352.43 | 1809.09 | 5152.20 | |
| E74 (Sim#1) | IRR de la inversion (s/flujos) | 4% | 20% | 49% | 30% |
| E74 (Sim#2) | IRR de la inversion (s/flujos) | 7% | 23% | 62% | |
| E74 (Sim#3) | IRR de la inversion (s/flujos) | 11% | 22% | 46% | |

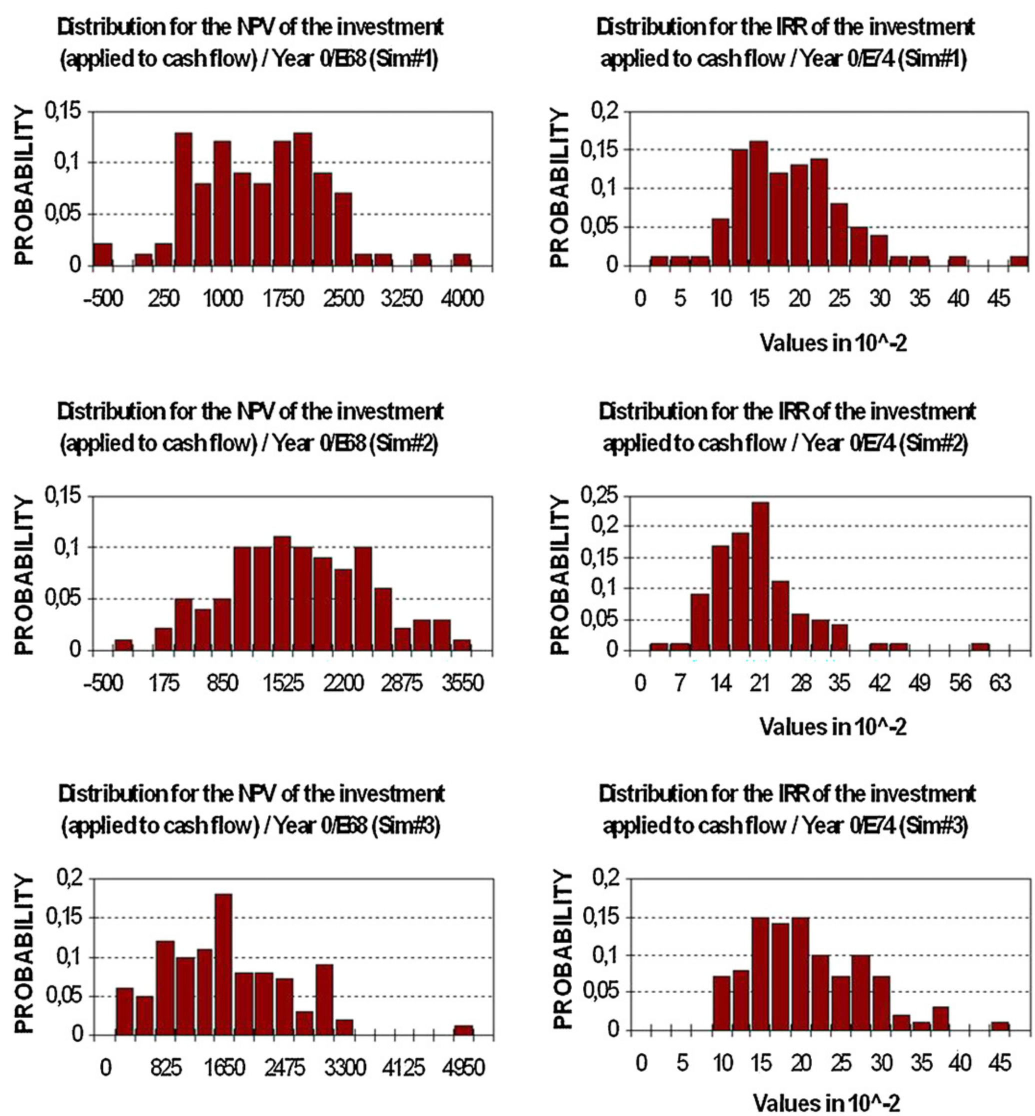



**Fig. 6.** Probability distributions of the two outputs obtained.

In each iteration, energy sale price was calculated as follows:

$$\text{Tariff}_i = \text{Market Price}_i + 0.5 \cdot \text{TMR}$$

### 4.3. Monte Carlo simulation

The method consists in generating a series of random numbers (in this case, one number for each random variable) which are transformed into another series of numbers formed by possible variable values, that is, in each iteration a value is randomly selected for each of the probability distributions of the variables allowing us to calculate the outputs, Net Present Value the Internal Rate of Return of the investment.

This process is repeated until we obtain the probability distribution for the aforementioned outputs. Therefore, the number of iterations must be sufficiently large to allow us to appreciate the possibility of occurrence of the different values. The computer simulation amasses registries for each specific value of the different profitability indexes and subsequently calculates the expected values and typical variance of each value, along with the corresponding histogram.

Table 7 shows the input variables that were considered as random in the simulation, with their respective, previously identified, probability distributions. Moreover, it was assumed that the velocities of the five turbines completely coincided with one another each year, in order to make the model more realistic. The simulation software [23] facilitates this process by introducing a variable correlation matrix.

Having defined the input variables, all that remains is to run the simulation. In this case, three simulations were performed, each involving 100 iterations. Moreover, current simulation packages allow us to work directly via an electronic spreadsheet, which speeds up the process considerably. We designed the spreadsheet for this project during analysis in conditions involving no uncertainty (Table 5). This will be used to simulate investment risk.

Table 8 presents a summary of the results of the simulation, with the mean and peak values for Net Present Value and Internal Rate of Return of the investment in each of the three simulations. In addition, Fig. 6 shows the probability distributions of the two outputs that were obtained.

## 5. Conclusions

The objective of this paper was, via a practical example, to study the applicability of Monte Carlo techniques in the analysis of the profitability of windfarm projects with a view to obtaining a plausible methodology to determine the risk of these types of investment. We also attempted to compare this type of analysis involving statistical simulation and the classical method of evaluating investment on the basis of the mean values of all input variables.

Therefore, we set up a model windfarm project, which has also allowed us to identify the basic parameters of current projects of this nature in Spain. The first step involved analysing profitability in conditions involving no uncertainty, considering all inputs as deterministic variables (Model Project). Subsequently, we carried out risk analysis via computer simulation, considering wind velocity, which determines output, and the market price of the energy (Simulated Project) as random variables.

Whilst the first analysis, employing traditional techniques, provided us with a single average value for each of the various indexes of the profitability of the investment, the risk analysis, consisting of three simulations involving 100 iterations, allowed us to generate probability distributions for the NPV and IRR in each simulation. Simply by observing these probability distributions, we become aware of the uncertainties that accompany our investment and of the fact that the probabilities of obtaining more or less profit are substantially the same.

The comparison of the two types of analysis reveals the exiguousness of the information provided by profitability analysis in conditions involving no uncertainty, the inability of this type of analysis to take the uncertainty associated with these types of projects into consideration and, therefore, the risk of making decisions in relation to an investment that are based exclusively on analysis of this nature.

In addition, we developed a procedure to transform the definitive investment inputs into random variables, with the corresponding probability descriptions, and to carry out project risk simulation via simulation software. It is therefore clear that, whilst in the past the use of these techniques was an overly complex process, they can now be applied with considerable ease, thereby becoming an extremely useful tool.

In short, it has been demonstrated that Monte Carlo sampling provides a practical method of finding the distribution of the NPV and IRR from the various random input variables. Given that it is also a powerful instrument when analysing sensibility and when testing different scenarios, which is necessary when investments are highly complex, it can be concluded that Monte Carlo sampling is an extremely competent approach in terms of the economic risk of windfarm projects.

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